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Suspended Ge cross-shaped microstructures for enhancing biaxial tensile strain

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Abstract

We demonstrate a novel suspended Ge cross-shaped microstructure for enhancing tensile strain biaxially. The strain and optical properties have been characterized by means of micro-Raman spectroscopy and micro-photoluminescence. We can systematically control the biaxial tensile strain by changing structural geometry. A maximum biaxial strain of 0.52% has been achieved.

1. Introduction

Optical interconnects are one solution for overcoming the limitations of metal wiring in both inter-chip and intra-chip communications. Although hybrid integration of III-V lasers on Si substrates by wafer bonding has had significant progress, the development of efficient light sources using group-IV semiconductors is still necessary. To date, Ge has become an important group-IV semiconductor as an active material due to its pseudo-direct gap behavior and compatibility with Si complementary metal oxide semiconductor processing. In order to utilize Ge as an active material, the application of tensile strain is vital [1]. The energy difference between the direct and indirect bandgaps can be reduced by the tensile strain, and the light emission through the direct transition can be dramatically enhanced as a consequence.

Recently, several techniques have been reported to introduce tensile strain in Ge. These include an automatically induced residual tensile strain during the growth on Si [2], the use of SiN stressor layers [3], and the combination of residual tensile strain and strain induced by microstructures [4,5]. This combination method is promising for enhancing the residual tensile strain, but to date only uniaxial tensile strain has been reported.

In this contribution, we demonstrate a novel suspended Ge microstructure in order to enhance the residual tensile strain *biaxially*. We characterize the strain field by means of micro-Raman (μ-Raman) spectroscopy and micro-photoluminescence (μ-PL) under atmospheric conditions at room temperature.

2. Sample and Fabrication

Figure 1(a) shows a schematic illustration of the Ge suspended cross-shaped microstructures. Four large pads are connected with four narrower arms forming a suspended central cross structure. Around the center of the cross, the residual biaxial strain is enhanced biaxially. The pads play a crucial role for this enhancement, as they can relax when the underlying buried oxide layer (SiO_2) is removed (thus shrinking and pulling on the central structure).

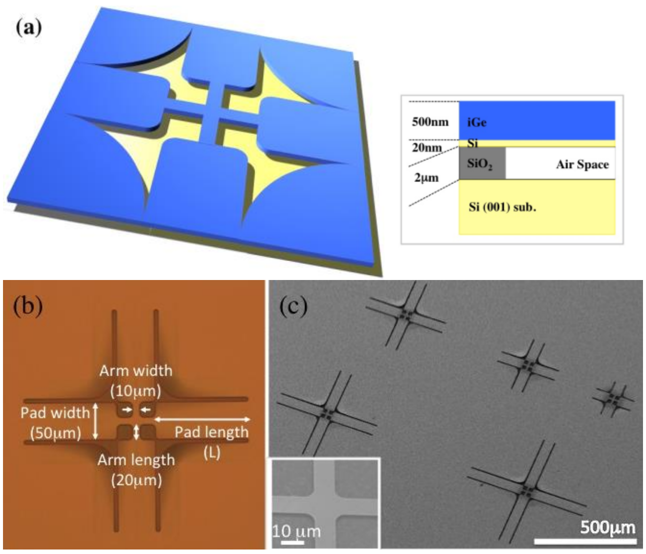

Fig. 1:(a) Schematic illustration of the suspended cross-shaped microstructure, (b) optical microscope image, and (c) SEM image of several structures of different sizes.

The sample used in this study is a 500 nm thick intrinsic Ge (iGe) layer grown (using chemical vapor deposition) on a SOI substrate (buried oxide layer: 2 μm). The microstructures were created by electron beam lithography, whereby the structure pattern was transferred into both the Ge and SOI layers by reactive ion etching with a CHF_3/O_2 mixture. Finally, the buried oxide layer was removed using a vapor-HF process to release the patterned Ge microstructures.

Figure 1(b) shows an optical microscope image of a fabricated structure (top view). The design parameters of the structures are as follows: The pad lengths have variation between 65 μm and 265 μm (in steps of 50 μm) to control the tensile strain. The pad width is 50 μm, and the arm width and length are 10 μm and 20 μm, respectively, fixed for all patterns. Scanning electron microscope (SEM) images of the fabricated microstructures are shown in Fig. 1(c). As can be seen in the inset of the figure, we are able to form a suspended cross of iGe in the pattern center, with the SiO_2 layer being cleanly removed.

3. Measurement and Discussion

μ-Raman spectroscopy was used to evaluate the local strain field of the fabricated microstructures with a continuous-wave laser (wavelength: 532 nm, spot size: ~1 μm). We used a pump power of 1 mW in order to achieve an appropriate signal-to-noise ratio for fitting whilst also minimizing heat effects. In figure 2(a) we present the Raman spectra measured at the center of the crosses of the suspended Ge microstructures (pad length: L=65 μm and 265 μm) in conjunction with the spectrum of the intrinsic non-stained bulk iGe as a reference. By fitting the spectra with a Lorentzian function, we are able to evaluate the relative Raman shift and have estimated the corresponding biaxial tensile strain using a strain-shift coefficient of 424 cm^{-1} [4]. Figure 2(b) shows the dependence of the estimated biaxial tensile strain on the pad length L. The strain increases with increasing L and shows a saturation tendency for longer pad lengths, which can be well reproduced by finite element simulation. A maximum strain of 0.52 % is obtained for the longest pad length (265 μm), corresponding to a 2.5 times enhancement of the tensile strain with respect to the un-patterned area (0.24 %).

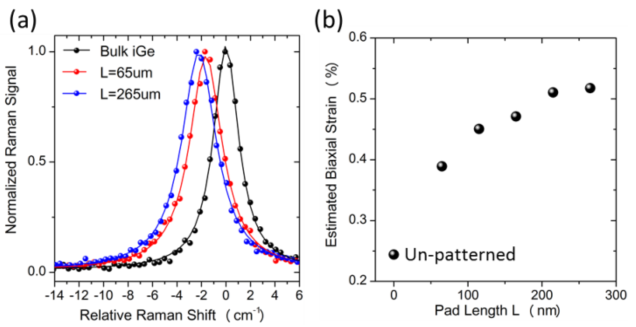

Fig. 2:(a) Pad size dependence of the normalized Raman spectra with fitting curves. (b) Biaxial tensile strain estimated from the Raman shift.

In order to further clarify the strain enhancement, we performed μ-PL measurements under excitation with a continuous-wave laser (wavelength: 740 nm, excitation power: 1 mW, spot size: ~1 μm). Figure 3(a) shows the normalized PL spectra measured at the center of the crosses in conjunction with both the spectra of an un-patterned area and the non-strained bulk iGe. The PL of the suspended Ge microstructures shifts towards lower energy systematically with increasing pad length (increasing strain). Two peaks appear in the PL spectra, corresponding to the direct transition between the conduction band and two separate valence bands (c-lk and c-hh) due to the strain. Figure 3(b) shows the dependence of the PL peaks for the microstructures with different pad lengths as a function of the biaxial strain estimated by Raman spectroscopy. The solid curves are theoretical estimations [6] and can be seen to be in fairly good agreement with the experiment, clearly demonstrating that the observed PL shift results from the strain variation.

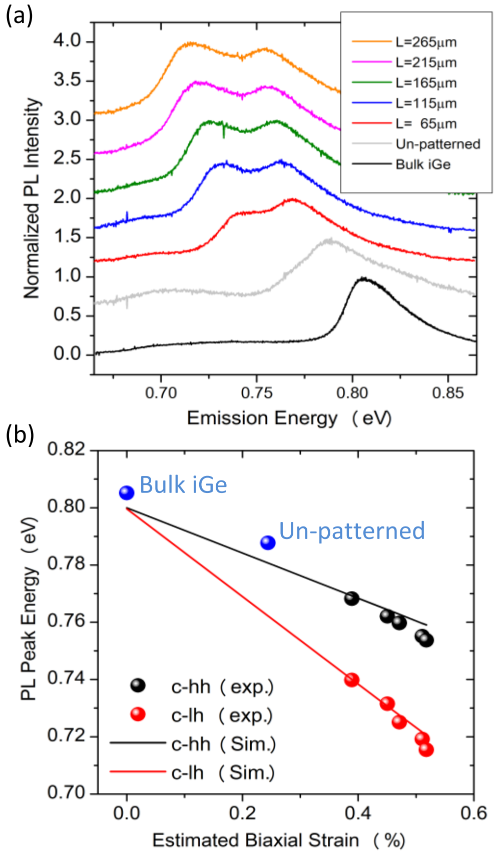

Fig. 3:(a) Normalized PL spectra measured at the center of the crosses. (b) PL peak energy as a function of the estimated biaxial strain. The red and black curves are theoretical ones.

4. Conclusions

We have successfully fabricated suspended Ge cross-shaped microstructures to enhance the biaxial tensile strain. A maximum strain of 0.52% has been achieved, corresponding a 2.5 times enhancement of the tensile strain with respect to the un-patterned area. This achievement is an important step towards the development of an efficient Ge light source in conjunction with n-type doping and optical cavities.

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References

[1] J. Liu *et al.*, *Photonics*, **1** (2014) 162.
[2] Y. Ishikawa *et al.*, *J. Appl. Phys.* **98** (2005) 013501.
[3] J. Jain *et al.*, *Nature Photon*. **6** (2012) 398.
[4] M. J. Suess *et al.*, *Nature Photon*. **7** (2013) 466.
[5] D. Nam *et al.*, *Nano. Lett.* 13 (2013) 3118.
[6] J. Liu *et al.*, *Phys. Rev. B* **70** (2004) 155309.